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Florian LUCA et Ravindranathan THANGADURAI

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On an arithmetic function considered by Pillai

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Résumé. Soit n un nombre entier positif et $p(n)$ le plus grand nombre premier $p \leq n$. On considère la suite finie décroissante définie récursivement par $n_1 = n$, $n_{i+1} = n_i - p(n_i)$ et dont le dernier terme, n_r, est soit premier soit égal à 1. On note $R(n) = r$ la longueur de cette suite. Nous obtenons des majorations pour $R(n)$ ainsi qu'une estimation du nombre d'éléments de l'ensemble des $n \leq x$ en lesquels $R(n)$ prend une valeur donnée k.

Abstract. For every positive integer n let $p(n)$ be the largest prime number $p \leq n$. Given a positive integer $n = n_1$, we study the positive integer $r = R(n)$ such that if we define recursively $n_{i+1} = n_i - p(n_i)$ for $i \geq 1$, then n_r is a prime or 1. We obtain upper bounds for $R(n)$ as well as an estimate for the set of n whose $R(n)$ takes on a fixed value k.

1. Introduction

Let $n > 1$ be an integer. Let $p(n)$ be the largest prime factor of n. Let $n_2 = n_1 - p(n_1)$. If $n_2 > 1$, let $n_3 = n_2 - p(n_2)$, and, recursively, if $n_k > 1$, we put $n_{k+1} = n_k - p(n_k)$. Note that if n_k is prime, then $n_{k+1} = 0$. We put $R(n)$ for the positive integer k such that n_k is prime or 1. Hence, we obtain a representation of n of the form

$$n = p_1 + p_2 + \cdots + p_r, \tag{1.1}$$

with $r = R(n)$, where $p_1 > p_2 > \cdots > p_r$ are primes except for the last one which might be 1.

The above representation of n was first considered by Pillai in [6] who obtained a number of interesting results concerning the function $R(n)$. Here, we extend some of Pillai's results on this function.

Since by Bertrand's postulate the interval $[x, 2x)$ contains a prime number for all $x \geq 1$, it follows that if $n_k > 1$, then $n_{k+1} \leq n_k/2$. This immediately implies that $R(n) = O(\log n)$. Pillai proved that the better estimate $R(n) = o(\log n)$ holds as $n \to \infty$. He also showed, under the

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Riemann Hypothesis, that the inequality $R(n) < 2\log\log n$ holds whenever $n > n_0$. Here, we remove the conditional assumption on the Riemann Hypothesis from Pillai's result and prove the following theorem.

Theorem 1.1. *The estimate*

$$R(n) \ll \log\log n$$

holds for all positive integers $n \geq 3$.

Pillai also showed that

$$\limsup_{n\to\infty} R(n) = \infty. \tag{1.2}$$

Our next result is slightly stronger than estimate (1.2) above. In what follows, we put $\log_k x$ for the function defined inductively as $\log_1 x = \log x$ and $\log_k x = \max\{1, \log(\log_{k-1} x)\}$ for $k > 1$. When $k = 1$, we omit the subscript. Note that if x is large, then $\log_k x$ coincides with the kth fold composition of the natural logarithm function evaluated in x.

Theorem 1.2. *Let* $k \geq 1$ *be any fixed integer. Then the estimate*

$$\#\{n \leq x \ : \ R(n) = k\} \ \asymp_k \ \frac{x}{\log_k x}$$

holds.

Theorem 1.2 shows that for any fixed k, the asymptotic density of the set of n with $R(n) \leq k$ is zero. This shows not only that estimate (1.2) holds, but that $R(n) \to \infty$ holds on a set of n of asymptotic density 1.

Pillai also conjectured that perhaps the inequality $R(n) \gg \log\log n$ holds for infinitely many n. We believe this conjecture to be false. Indeed, a widely believed conjecture of Cramér [2] from 1936, asserts that if $x > x_0$, then the interval $[x, x + (\log x)^2]$ contains a prime number. If true, this implies that if $n_k > x_0$, then $n_{k+1} < (\log n_k)^2$. Let $f(n)$ be the function which associates to each integer $n > x_0$ the minimal number of iterations of the function $x \mapsto (\log x)^2$ required to take n just below x_0. Then Cramér's conjecture implies that $R(n) \leq f(n) + O(1)$, where the constant implied in $O(1)$ can be taken to be $\max\{R(n) : n \leq x_0\}$. Let us take a look at these iterations. Assume that n is large. We then have $n_1 = n$, $n_2 \leq (\log n)^2$, $n_3 \leq (\log n_2)^2 \leq (2\log(2\log n))^2 < 8(\log\log n)^2$. Inductively, one shows that if k is fixed and n is sufficiently large with respect to k, then the inequality $n_k < 8(\log_k n)^2$ holds. Since k is arbitrary, we conclude that $f(n) = o(\log_k n)$ holds with any fixed $k \geq 1$ as $n \to \infty$, so, in particular, the inequality $f(n) \gg \log\log n$ cannot hold for infinitely many positive integers n. Let us observe that the weaker assumption that the interval $[x, x + \exp((\log x)^{1/2})]$ contains a prime for all $x > x_0$ will easily lead to the conclusion that $R(n) = O(\log_3 n)$. Indeed, in this case we have $\log n_{k+1} \leq (\log n_k)^{1/2}$, whenever $n_k > x_0$. In particular, $\log n_{k+1} \leq (\log n)^{1/2^k}$, whenever $n_{k+1} > x_0$. This implies easily that for some k of size at most $(\log\log\log n)/\log 2 + O(1)$ we have $n_{k+1} < x_0$, so that $R(n) = O(\log_3 n)$.

Pillai also looked at the sequence of local maxima (in modern terms also called *champions*) for the function $R(n)$. Recall that n is called a *champion* if $R(m) < R(n)$ holds for all $m < n$. Let $\{t_k\}_{k\geq 1}$ be the sequence of champions. Pillai showed that $t_1 = 1$ and that the recurrence $t_{k+1} = p(t_{k+1}) + t_k$ holds for all $k \geq 1$. Furthermore, t_k and t_{k+1} have different parities for all $k \geq 1$. He also showed that $\{t_k\}_{k\geq 1}$ grows very fast, namely that for each positive constant A one has $t_{k+1} \gg_A t_k(\log t_k)^A$. He also calculated the first 4 values of the sequence $\{t_k\}_{k\geq 1}$ obtaining

$$t_1 = 1, \quad t_2 = 4 = 3 + 1, \quad t_3 = 27 = 23 + 4, \quad t_4 = 1354 = 1327 + 27.$$

He mentioned (seventy years ago!) that it is perhaps possible to compute t_5 but not t_6. Consulting Thomas Nicely's [5] tables of prime gaps, we get

$$t_5 = 401429925999155061 = 401429925999153707 + 1354$$

and Cramér's conjecture implies that $t_6 > \exp(4 \cdot 10^8)$, so indeed it is perhaps not possible to compute t_6.

2. Proof of Theorem 1.1

For the proof of the fact that $R(n) < 2\log\log n$ for $n > n_0$ under the Riemann Hypothesis, Pillai used the known consequence of the Riemann Hypothesis that for each $\delta > 0$, there is some x_δ such that when $x > x_\delta$, the interval $[x, x + x^{1/2+\delta}]$ contains a prime number.

In the same year as Pillai's paper [6] appeared, Hoheisel proved his famous theorem about Prime Number Gaps.

Theorem 2.1 ([4]). *There exist absolute constants $\theta \in (0,1)$ and N_0 such that for every integer $n \geq N_0$, the interval $[n - n^\theta, n]$ contains a prime number.*

The best known $\theta = 0.525$ is due to Baker, Harman and Pinz [1]. The proof of Theorem 1.1 follows easily from Pillai's arguments by replacing the prime number gaps guaranteed by the Riemann Hypothesis with Hoheisel's result.[1]

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[1]It seems likely that Pillai was not aware of Hoheisel's paper [4].

Let $n_1 \geq N_0$. By Theorem 2.1, $p(n_1) > n - n^{\theta}$. Thus, the chain of inequalities

$$\begin{aligned} n_2 &= n_1 - p(n_1) < n_1 - n_1 + n_1^{\theta} = n_1^{\theta}; \\ n_3 &= n_2 - p(n_2) < n_2^{\theta} < n_1^{\theta^2}; \\ n_4 &< n_1^{\theta^3}; \\ &\cdots\cdots\cdots \\ n_{\ell+1} &< n_1^{\theta^{\ell}} \end{aligned}$$

holds as long as $n_\ell \geq N_0$. We now let ℓ be that integer such that $n_{\ell+2} < N_0 \leq n_{\ell+1}$. We then have

$$n_1^{\theta^{\ell}} \geq N_0,$$

therefore

$$\theta^{\ell} \log n_1 \geq \log N_0,$$

which implies that

$$\ell \log \theta + \log\log n_1 \geq \log\log N_0.$$

Hence,

$$\log\log n_1 \geq \ell \log(1/\theta),$$

which in light of the fact that $\theta \in (0,1)$ gives

$$\ell \leq \frac{\log\log n_1}{\log(1/\theta)}.$$

Put $b = \max_{1 \leq m \leq N_0}\{R(m)\}$. Trivially, $b \leq \pi(N_0)$. Thus,

$$R(n_1) \leq \ell + 1 + b < \frac{\log\log n_1}{\log(1/\theta)} + 1 + b \ll \log\log n_1,$$

which is the desired inequality.

3. Proof of Theorem 1.2

For every prime number p we put p' for the next prime following p. The following result is certainly well-known but we shall supply a short proof of it.

Lemma 3.1. *For $2 \leq y \leq \log x$, put*

$$\mathcal{P}(x,y) = \left\{p \leq x : p' - p \notin [y^{-1}(\log x), y(\log x)]\right\}.$$

Then,

$$\#\mathcal{P}(x,y) \ll \frac{\pi(x)}{y}. \tag{3.1}$$

Proof. We first look at the primes $p \le x$ which are in $\mathcal{P}(x,y)$ and $p'-p > y\log x$. The interval $[1,x]$ is contained in the union of the subintervals $[(i-1)y\log x, iy(\log x)]$ for $i = 1,2,\ldots,\lfloor x/(y\log x)\rfloor + 1$. Since $p'-p > y(\log x)$, each one of the above intervals can contain at most one such prime p. Thus, the number of such primes p does not exceed

$$\begin{aligned}\#\{p \le x \ : \ p'-p > y(\log x)\} &\le \lfloor x/(y\log x\rfloor + 1 \le 2x/(y\log x)\\ &\ll \pi(x)/y. \end{aligned} \tag{3.2}$$

We next look at the primes $p \le x$ which are in $\mathcal{P}(x,y)$ and $p'-p = h < z = y^{-1}(\log x)$. We fix h and look at the set of primes $p \le x$ such that $p+h$ is also prime. We write $\mathcal{A}_h(x)$ for this set. By Brun's sieve (see, for example, [3, Theorem 5.7]), we have

$$\#\mathcal{A}_h(x) \ll \frac{x}{(\log x)^2}\frac{h}{\phi(h)}.$$

Summing up over all the acceptable values of $h \le z$, we get that

$$\begin{aligned}\#\{p \le x \ : \ p'-p < z\} &\le \sum_{1\le h\le z} \#\mathcal{A}_h \le \frac{x}{(\log x)^2}\sum_{1\le h\le z}\frac{h}{\phi(h)}\\ &\ll \frac{xz}{(\log x)^2} \ll \frac{\pi(x)}{y}. \end{aligned} \tag{3.3}$$

In the above estimates, we used the known fact that the estimate

$$\sum_{1\le h\le t}\frac{h}{\phi(h)} \ll t$$

holds for all $t \ge 1$ (see, for example, [7]). The desired conclusion follows now immediately from estimates (3.2) and (3.3). □

Proof of Theorem 1.2. We put $\mathcal{R}_k = \{n : R(n) = k\}$ and $\mathcal{R}_k(x) = \mathcal{R}_k \cap [1,x]$. We prove the theorem by induction on k having as a base the case $k=1$ for which the assertion is immediate by the Prime Number Theorem.

Assume that $k \ge 2$. We first deal with the upper bound on $\#\mathcal{R}_k(x)$. We have, by the induction hypothesis,

$$\begin{aligned}\#\mathcal{R}_k(x) &= \#\{n = p+m \le x \ : \ R(m) = k-1,\ p \le n < p'\}\\ &= \sum_{p\le x}\#\{m \le p'-p \ : \ R(m) = k-1\}\\ &\le \sum_{p\le x}\#\mathcal{R}_{k-1}(p'-p) \ll_k \sum_{p\le x}\frac{(p'-p)}{\log_{k-1}(p'-p)}. \end{aligned} \tag{3.4}$$

We split the last sum above at $z = (\log x)^{1/3}$. If $p' - p > z$, then $\log_{k-1}(p' - p) \gg_k \log_k x$, therefore

$$\sum_{\substack{p \le x\\ p'-p>z}} \frac{(p'-p)}{\log_{k-1}(p'-p)} \ll_k \frac{1}{\log_k x} \sum_{p\le x}(p'-p) \ll \frac{x}{\log_k x}, \tag{3.5}$$

where for the last inequality above we used the fact that the intervals $[p, p')$ for $p \le x$ are disjoint and their union is contained in $[1, 2x]$ by the Bertrand postulate. For the range $p' - p \le z$, we proceed as in the proof of Lemma 3.1 by first fixing $h \le z$ and looking at the primes $p \in \mathcal{A}_h(x)$. The proof of Lemma 3.1 shows that

$$\begin{aligned}\sum_{p\in\mathcal{A}_h(x)} \frac{(p'-p)}{\log_{k-1}(p'-p)} &\ll \sum_{p\in\mathcal{A}_h(x)} h \le h\#\mathcal{A}_h \ll \frac{x}{\log x}\frac{h^2}{\phi(h)}\\ &\ll \frac{xz}{\log x}\frac{h}{\phi(h)},\end{aligned}$$

therefore

$$\sum_{\substack{p \le x\\ p'-p\le z}} \frac{(p'-p)}{\log_{k-1}(p'-p)} \ll \frac{xz}{\log x}\sum_{h\le z}\frac{h}{\phi(h)} \ll \frac{xz^2}{\log x} = \frac{x}{z} \ll \frac{x}{\log_k x}. \tag{3.6}$$

Estimates (3.4), (3.5) and (3.6) imply the desired upper bound on $\#\mathcal{R}_k(x)$.

We now turn our attention on the lower bound for $\#\mathcal{R}_k(x)$. We proceed again by induction on $k \ge 1$. Let $c_1 > 0$ be the constant implied in inequality (3.1) and let $y = 2c_1$. Then $\#\mathcal{P}(x, y) \le \pi(x)/2$. Let $p \le x$ be a prime not in $\#\mathcal{P}(x, y)$ and $m \in \mathcal{R}_{k-1}((\log x)/y)$. Put $n = m+p$. Then $n = m+p < (\log x)/y+p < p'$, therefore $p = p(n)$. Thus, $R(n) = 1+R(m) = k$. The number of pairs (p, m) with the above properties is

$$\begin{aligned}&\ge (\pi(x) - \#\mathcal{P}(x,y))\#\mathcal{R}_{k-1}((\log x)/y) \gg_k \frac{\pi(x)\log x}{\log_{k-1}((\log x)/y)}\\ &\gg_k \frac{x}{\log_k x}.\end{aligned}$$

Each such pair (p, m) leads to a value of $n \le x + (\log x)/y \le 2x$. Furthermore, distinct pairs (p, m) lead to distinct values of n, for if $p+m = p_1+m_1$ for some $(p, m) \ne (p_1, m_1)$ then, assuming say that $p_1 > p$, we get

$$p' - p \le p_1 - p = m - m_1 < m < (\log x)/y,$$

which is impossible. Hence, $p_1 = p$ and since $p + m = p_1 + m_1$, we also get $m = m_1$, which is impossible since the pairs (p, m) and (p_1, m_1) were distinct. Thus, we showed that $\#\mathcal{R}_k(2x) \gg_k x/\log_k x$, which implies the desired lower bound.

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Florian Luca
Mathematical Institute
UNAM, Ap. Postal
61-3 (Xangari), CP 58089
Morelia, Michoacán, Mexico
E-mail: fluca@matmor.unam.mx

Ravindranathan Thangadurai
Harish-Chandra Research Institute
Chhatnag Road, Jhunsi
Allahabad 211 019, India
E-mail: thanga@mri.ernet.in